

Cooling and Cooling-down MgB_2 and HTS Magnets using a Hydrogen Thermal Siphon Loop and Coolers operating from 15 K to 28 K

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Abstract— MgB_2 and HTS magnets might be better being cooled using a cooler if they operated in the temperature range from 15 K to 40 K. Liquid neon has been considered as a fluid for cooling such magnets. Neon can only be used in the upper part of the temperature range; neon is scarce; and neon has poor thermal properties when compared to hydrogen or helium. For many MgB_2 and HTS magnet applications, liquid hydrogen is an ideal working fluid. Liquid hydrogen has a high heat of vaporization, a high specific heat, and excellent heat transfer properties. This paper describes the kind of thermal siphon cooling loop that can be used for cooling-down a superconducting magnet and keeping it cold in the range from 15 K to 28 K. This report will present a method for using hydrogen gas to cool-down and cool a magnet that is relatively safe.

Index Terms— MgB_2 and HTS magnets, LH_2 Cooling Loop

I. INTRODUCTION

The advent of high temperature superconductors (HTS) meant that magnets could be operated at temperatures that are higher than that of liquid helium. [1]. In general, magnets fabricated from Nb-Ti and Nb_3Sn operate at temperatures in the range from 1.8 K to 8 K. If these magnets are cooled using small coolers, the operating temperature range is restricted to 3.7 to 8 K. If one uses a superconductor such as MgB_2 or HTS conductors such as Bi2212 , Bi2223 , or YBCO, one may be able to extend the operating temperature range for the magnet to about 40 K and still have almost no resistance.

Two stage coolers can operate at temperatures well above 4.2 K. Some models of both two-stage GM and pulse tube coolers have been tested with their second stage temperatures up to 250 K [2]. These coolers can be used to cool-down a magnet as well as allow it to operate at its design operating temperature. The connection between the cooler second-stage cold head and the magnet is important, particularly at low temperatures [3]. Two methods of connecting the cooler to the magnet are commonly used; 1) a high RRR copper or aluminum connector or 2) a thermal-siphon cooling-loop that works with both with a gas and two-phase cryogenics [3], [4].

For small magnets using direct conduction cooling from the cold head to the magnet (the so-called cryogen free option) makes sense as long as the temperature drops between the parts of the magnet farthest from the cooler to the magnet cold head are acceptable. When cooling and cooling down a large magnet, the copper or aluminum connector becomes a limiting factor. The temperature drop is proportional to the connector length and thermal conductivity and inversely proportional to the connector cross-section area.

When a magnet is large, both in diameter and length, the temperature drops are much higher. An alternative method of delivering the cooling from the cold head to the magnet is a thermal-siphon cooling-loop combined with a high RRR copper or aluminum sheath can greatly reduce the temperature drop between the farthest points in a magnet to the cooler cold head. The same thermal-siphon cooling-loop can be used to cool-down the magnet as well as keep it cold, provided the cooling system is designed for cooling down a magnet and liquefying the cryogen that is within the loop.

II. WHY H_2 INSTEAD OF HE OR NE IN THE LOOP?

A typical thermal-siphon cooling-loop has a condenser that condenses a cryogenic fluid and the magnet, which acts as the evaporator for the cooling loop. The flow in the loop is driven by natural convection, with the density of the fluid leaving the condenser greater than the density of the fluid going back up to the condenser from the magnet. For fluids except helium, the temperature range of operation for the cooling loop is between the triple-point (where liquid, gas, and solid can coexist) to the critical-point (where distinct liquid and gas phases cease to exist). The fluid that is exception is helium 4 because the triple-point is the coexistence of two liquid phases and the gas phase. The solid helium can only occur at pressures above the critical pressure.

TABLE I compares the parameters of helium 4, para hydrogen, and neon [3], [5]. The useful operating points for these three gases (in the two-phase region) are between their triple point temperatures and their critical temperatures. A two-phase thermal siphon loop for helium is limited at the lower temperature end by the cooler, so the useful operating temperature range is from 3.2 to 4.8 K. For hydrogen the useful two-phase operating temperature range is from 15 K to ~30 K. For neon the useful two-phase operating temperature range is from 25 K to 40 K. TABLE I contains a number of useful parameters for determining the relative performances of the three gases when used in a cooling loop [5].

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TABLE I. PARAMETERS OF HELIUM, HYDROGEN, AND NEON [5]

Parameter	Fluid		
	He	H ₂	Ne
Triple Point T (K)	2.17	13.81	24.57
Triple Point P (kPa)	5.1	7.0	42.3
Boiling T T _b at 101.3 kPa (K)	4.22	20.4	27.2
Liquid Density at T _b (kg m ⁻³)	125	70.8	1212
Critical T (K)	5.19	32.3	44.4
Critical P (kPa)	221	1292	2710
Heat of Vaporization (J g ⁻¹)	20.9	442	86.0
C _p Liquid at T _b (J g ⁻¹ K ⁻¹)	~2.5	~9.8	~0.44
C _p Gas at T > 2T _b (J g ⁻¹ K ⁻¹)	~5.2	~14.2	~1.03
Enthalpy at 293 K (J g ⁻¹)	~1530	~4300*	~360
k _f Liquid at T _b (W m ⁻¹ K ⁻¹)	0.027	0.119	<0.04
k _f Gas at T _b (W m ⁻¹ K ⁻¹)	0.011	0.021	0.014
μ liquid at T _b (kg m ⁻¹ s ⁻¹)	3.5x10 ⁻⁶	1.3x10 ⁻⁵	~7x10 ⁻⁵
μ gas at T _b (kg m ⁻¹ s ⁻¹)	0.9x10 ⁻⁶	1.1x10 ⁻⁶	4.3x10 ⁻⁶
Max Nuc Boil Q (W m ⁻²) [6]	~8000^	~90000^	?
Film Boiling h _c (W m ⁻² K ⁻¹)	~670 [7]	~330 [7]	?
Max Condensation Q (W m ⁻¹)	~1000	~4000	~2000
Liquid to Gas Expansion Ratio	702	793	1344
Liquid Expansivity at T _b (T ⁻¹)	~0.21	~0.02	~0.014

* The ortho-to-para phase change transition heat is not included.

When one looks at TABLE I, one sees that hydrogen has a much larger heat of vaporization than either helium or neon. For a given amount of heat removed by a thermal-siphon cooling-loop, the mass flow of hydrogen will be much lower than for helium or neon. This translates to lower pressure drops in the thermal-siphon circuit. The density of hydrogen is roughly one half that of helium. The lower density of hydrogen contributes to increasing the pressure drop, but the effect is not as large as the effect of the reduced mass flow.

The viscosity of hydrogen is higher than that of helium. This combined with a lower mass flow means that the flow is more likely to be laminar. The thermal conductivity of liquid hydrogen is a factor of 4.4 higher than for liquid helium. The thermal conductivity of helium gas at 20 K is comparable to that of hydrogen gas. In terms of the liquid and gas thermal conductivity neon is unlikely to be any better than helium. (Helium gas at 27.2 K has a larger thermal conductivity than neon at the same temperature.) Liquid and gaseous hydrogen is a better heat transfer agent than neon or helium.

When a magnet operates at 20 K instead of 4 K, the temperature drop between the magnet and the cooler cold head can be higher. The peak nucleate boiling heat flux for H₂ is over an order of magnitude higher than for He. The condensation heat flux is also higher. The temperature drop for a hydrogen thermal-siphon loop can be kept below 0.5 K. The temperature drop between a large magnet and the cooler cold head will be higher for a cryogen free cooling.

Given the scarcity of neon and its high liquid to gas expansion ratio, neon is not an attractive option. The real negative with hydrogen in a thermal-siphon loop is its flammability. Methods for dealing with the flammability of hydrogen are presented later in this report.

III. THERMAL-SIPHON LOOP SUITABLE FOR HYDROGEN

Figure 1 shows a schematic of a magnet being cooled using a single cooler. The condenser heat exchanger, at the top, cools the hydrogen before it enters the magnet cooling tubes at the bottom of the magnet. If the magnet is being cooled down, the hydrogen warms up as it goes up around the magnet coils to return to the condenser heat exchanger at the top. Hydrogen entering the condenser enters at the top. The hydrogen sinks as it is cooled and leaves the heat exchanger at the bottom. The cold hydrogen enters the magnet cooling tubes at the bottom of the magnet where it is warmed up and rises. The driving pressure for the cooling loop is proportion to the vertical distance between the bottom of the condenser heat exchanger and the bottom of the magnet. The driving pressure is also proportional to the difference in the density of the hydrogen stream going minus the density of the hydrogen stream going up (back to the top of the condenser heat exchanger). The duct flow is driven by natural convection.

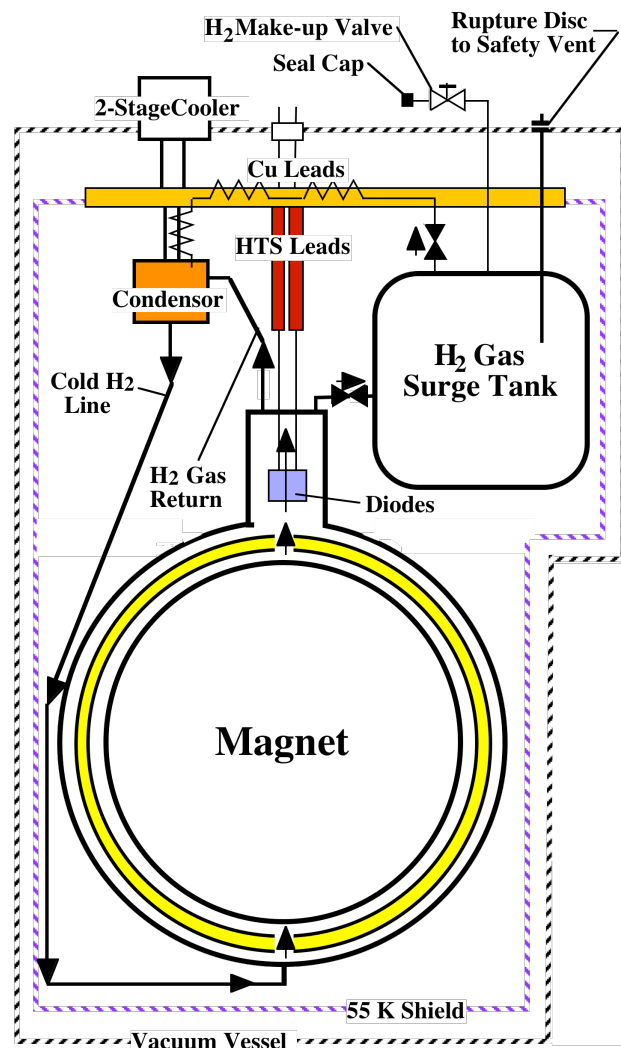


Figure 1. The cooling and cool-down circuit for an MgB₂ or HTS magnet using a liquid hydrogen cooling loop. The circuit shown uses a single two-stage cooler that is capable of delivering cooling at 4.2 K. The surge tank for the hydrogen is shown as being inside of the 55 K shield. This circuit can be used with multiple coolers.

Also shown in Figure 1 is the storage tank for the hydrogen. The system shown in Figure 1 is pressurized at room temperature (293 K). The pressure in the surge tank and the flow circuit goes down as the magnet cools down from room temperature. When the liquid hydrogen pipes are filled with liquid, the surge tank pressure can be within 3 kPa of the vapor pressure of the liquid hydrogen within the system. Once the magnet is cold and filled with liquid hydrogen, the condenser heat exchanger condenses the gas that is boiled due to heat put into the cryostat. This heat comes from a number of sources that include; 1) the radiation and conduction heat to the magnet and cooling system cryostat, 2) heating within the HTS or MgB₂ conductors due to resistive heating, 3) magnet coil and mandrel AC losses, and 4) the control heater that controls the system pressure and the magnet temperature.

The concept of cooling something down using a thermal-siphon loop has been demonstrated by LBL [8]. Cooling a magnet down with a cooler using a thermal-siphon cooling loop has been proposed for the cyclotron gas stopper magnet system at Michigan State University [9]. The cyclotron gas stopper magnet will be tested in the winter of 2014.

A few equations are useful for understanding how a thermal siphon cooling system works. In order for a thermal siphon system to work the pressure due to the density difference between the cold stream going down and the warm stream going up times the vertical distance from the bottom of the condenser heat exchanger and the point where the cold gas enters the bottom of the magnet cryostat must be greater than the pressure drop in the loop when the fluid is flowing. The maximum available driving pressure in the loop is low (from 1 to say 30 Pa). If the pressure-drop ΔP is too high relative to the available driving pressure (the density difference $\delta\Gamma$ times the height H), the desired mass flow M cannot be maintained. For a typical circuit, if the available pressure head is too low, the circuit will still flow (if it is properly oriented with respect to gravity), but the mass flow in the circuit will lower than desired. The pressure drop equations are as follows [10];

$$\Delta P = \Delta P_M + \Delta P_f, \quad (1)$$

where ΔP_M is the momentum term and ΔP_f is the duct friction term. The momentum term ΔP_M for a duct with an effective diameter D_E , ($D_E = [4A_c/\pi]^{0.5}$, with A_c the duct area.), a fluid density Γ , and a mass flow M takes the following form:

$$\Delta P_M = \frac{8M^2}{\pi^2 \Gamma D_E^4}. \quad (2)$$

The friction term depends on whether the flow is laminar or turbulent. Laminar flow occurs at low Reynolds number Re is < 1500 , whereas turbulent flow occurs at $Re > 5000$. In between is a transition region, which can be either laminar or turbulent. The $Re = 4MD_H/(\pi D_E^2 \mu)$, where D_H the hydraulic diameter is $4A_c/P$, where A_c is the duct area and P is the duct wetted perimeter. For round ducts $D_H = D_E$.

The friction term for a smooth pipe takes the following

forms depending on whether the flow is laminar or turbulent;

$$\Delta P_f = \frac{128M\mu}{\pi \Gamma D_E^2} \frac{L}{D_H}, \text{ when the flow is laminar, and} \quad (3a)$$

$$\Delta P_f = 0.175\pi \frac{8}{\pi^2} \frac{M^{1.8} \mu^{0.2}}{\Gamma D_E^{3.2}} \frac{L}{D_H^{1.2}}, \quad (3b)$$

when the flow is turbulent. L is the length of the duct. The friction term doesn't dominate until the value of L/D_H is large (say > 500). In the transition region, one should choose the larger of the two friction terms for design purposes. For most of the cases of interest the friction term can be ignored.

From the equations (1) through (3b) it is clear that the density term is important. If one pressurizes the circuit during a cool-down by a factor of two, the ΔP goes down a factor of two while the driving pressure goes up a factor of two. As a result the mass flow goes up. During normal operation the mass flow for hydrogen is a factor of 20 lower than it is for helium at the same heat load. While cooling down, the mass flow will go down a factor of 3, while the density Γ goes down a factor of two. For hydrogen, the ΔP will be about four times lower. A system that can be cooled down with helium in the loop will cool-down with hydrogen in the thermal-siphon loop. The other factors that affect cooling down the magnet are 1) the vertical distance between the condenser and the magnet cryostat bottom, 2) the ID of the pipe from the condenser to the magnet bottom, 3) the insulation quality on the pipe from the condenser to the magnet bottom, 4) the cooler second stage cooling, and 5) the number of coolers. An important advantage of using a thermal-siphon connector between the magnet and the coolers is the fact that the HTS leads [11] and the cooler [12] will be in a lower magnetic field region than they would be with a copper connector.

Figure 2 shows the temperature of a 1100 kg cold mass (copper and stainless steel) as function of time based on using a single PT410 cooler that generate 1 W at 4.2 K while generating 40 W at 45 K while operating on 60 Hz power.

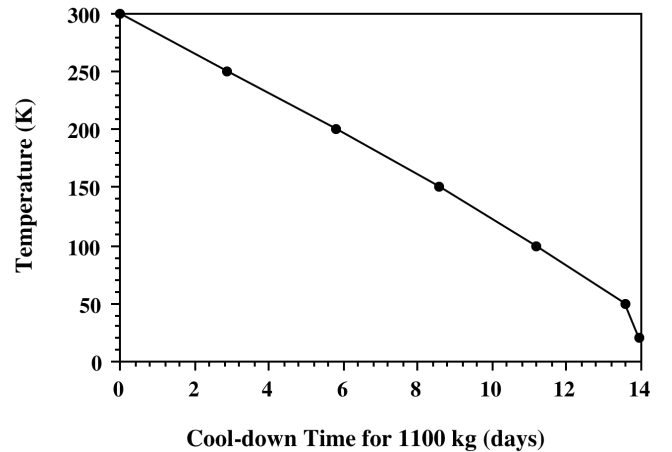


Figure 2. The calculated temperature of 1100 kg of copper and stainless steel as a function of time when it is cooled down with a hydrogen thermal-siphon cooling loop attached to a condenser attached to a single PT410 cooler.

The cool-down time is proportional to the total thermal energy in the cold mass. 1100 kg of copper and 304-Stainless steel contains about 90 MJ of thermal energy at 300 K. The thermal energy remaining at 20 K is 35 kJ. If the cold mass is pre-cooled to 100 K using liquid nitrogen, the cool-down time is reduced to about 3 days. The cool-down time is inversely proportional to the number of coolers and the cooling of each cooler at 4.2 K. If three PT415 coolers were used the cool-down time from 300 K to 20 K would be 3.1 days for 1100 kg.

The liquid hydrogen volume in the cooling system should be kept small (<3 liters). The time needed to liquefy 3 liters of hydrogen using only first-stage pre-cooling is less than 6 hours using a single PT410 cooler [13]. Using a single two-stage pulse tube cooler, with a circuit that pulls cooling off of the pulse tubes and regenerator tubes (as shown in Fig.1) can reduce the liquefaction time for 3 liters of hydrogen by a factor of 1.5 to 2. Despite the large amount of sensible heat that hydrogen has, a liter of hydrogen is easier to liquefy with a cooler than a liter of helium.

IV. PASSIVE HYDROGEN SAFETY

The hydrogen thermal-siphon cooling-loop shown in Fig. 1 has a passive safety system. The loop is filled with hydrogen gas at room temperature and sealed. The charging pressure of the loop is dependent on the surge volume, the liquid hydrogen volume and the volume of cold hydrogen gas in the system when it is operating. The system as shown in Fig.1 has the surge tank inside of the vacuum vessel and the 55 K shield. This is a reasonable solution if the total volume of liquid hydrogen in the system is < 3 liquid liters. Except for the charging line and the line that goes to the rupture disc all of the hydrogen system is separated from the air by vacuum. The charging valve and the rupture disc, which feeds a nitrogen gas vent tube could be in vacuum or in an atmosphere of nitrogen or argon gas. If the surge volume is too large, the surge tank could be moved outside of the building housing the magnet. The tank used outside of the building could be a stainless steel version of a standard propane tank. There are many arguments that suggest that hydrogen is safer than methane, propane or gasoline, despite the broad range of flammability in air [14].

If the design liquid hydrogen volume is 3 L at 20 K and the cold hydrogen gas volume is 2 L at 20 K, the surge tank could have a volume of 150 L. The charge pressure for the system would be just over ~1.7 MPa (250 psia) at 293 K. If the surge tank is larger, the charge pressure is lower. The tank and all of the piping would have to be designed in accordance with the flammable gas pressure vessel code. Ideally the piping and vessel stress should be less than the yield stress at four times the charge pressure. The tank and piping should not be subject to hydrogen embrittlement.

What happens if the magnet quenches? Energy in the magnet coil boils the hydrogen in the system and returns it to the hydrogen surge tank. If the 1100 kg is subjected to a sudden release of 5 MJ of energy, the system temperature will go up to ~75 K. A single PT410 cooler will cool the system back down and re-liquefy the hydrogen in ~2 days.

V. SOME CONCLUDING COMMENTS

Hydrogen is a viable working fluid for a thermal-siphon cooling loop that can be used to cool an MgB_2 or an HTS magnet operating in the temperature range from 15 K to 30 K. Hydrogen has a large heat of vaporization, so for a given heat load, the mass flow through a cooling loop is a factor of 20 lower than for a helium cooling loop during normal two-phase cooling loop operation. In terms of its heat transfer properties hydrogen is superior to either helium or neon in their respective operating temperature ranges. Hydrogen has about three times the sensible heat from 20 K to 293 K as helium over the same temperature range. This added sensible heat doesn't include the ortho-to-para transition heat. Therefore, during a cool-down the mass flow through the cooling loop is a factor of three lower than for a comparable helium cooling loop. A magnet cool-down should be easier with hydrogen.

Hydrogen safety is an issue, but a passive system such as is shown in Fig. 1 is far safer than a system when hydrogen is put into the system and taken out of the system during normal operation. The system shown in Fig. 1 can withstand a magnet quench or a rapid magnet warm up to 300 K without venting hydrogen.

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